PLASMA CHANNELS AND ACCELERATOR APPLICATIONS – A TUTORIAL

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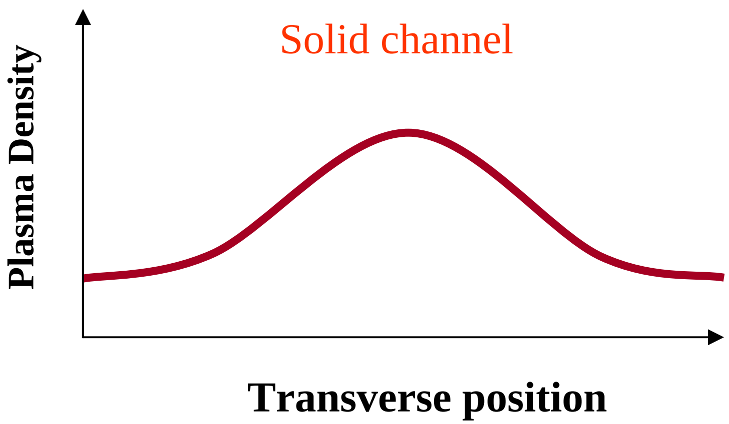
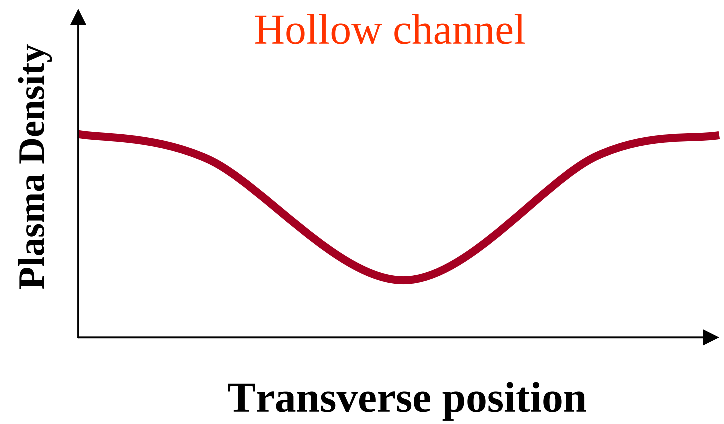
OUTLINE

- Introduction to plasma channels
- Channel creation methods
- Optical guiding in channels
- Applications to laser wakefield accelerators
- Applications to beam-driven plasma wakefield accelerators
- Summary

INTRODUCTION TO PLASMA CHANNELS

- Definition: a preionized column of plasma with a transverse variation in plasma density





- Important properties
  - Can provide focusing/guiding of optical or particle beams
  - Can provide accelerating medium for plasma-based accelerators
- Note: not considering non-preionized cases (self-channeling)

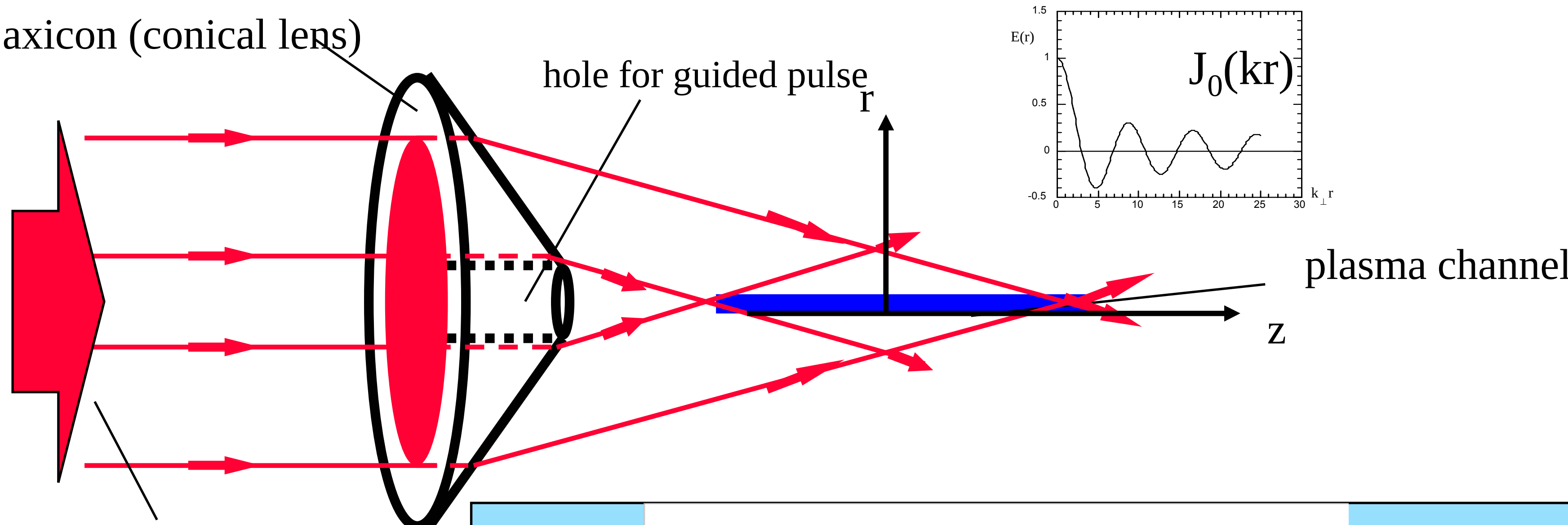
PLASMA CHANNEL GENERATION METHODS

- Laser-heated plasma hydro shock
- Plasma hydro shock with clusters
- Ablative-wall capillary discharge
- Gas-filled slow capillary discharge
- Gas-filled fast capillary discharge (z-pinch)
- Open discharges
- Self-guided (relativistic) laser pump pulse (hydro shock)
- Direct laser ionization

  – *Discussed in next section*

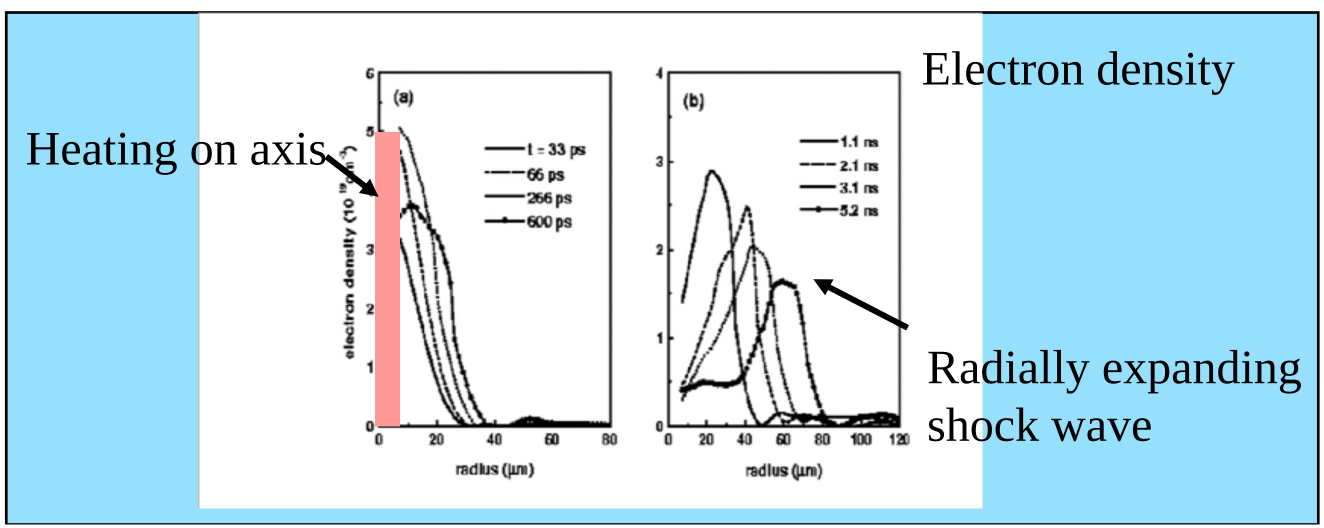
LASER-HEATED PLASMA HYDRO SHOCK

C. G. Durfee, III and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993)

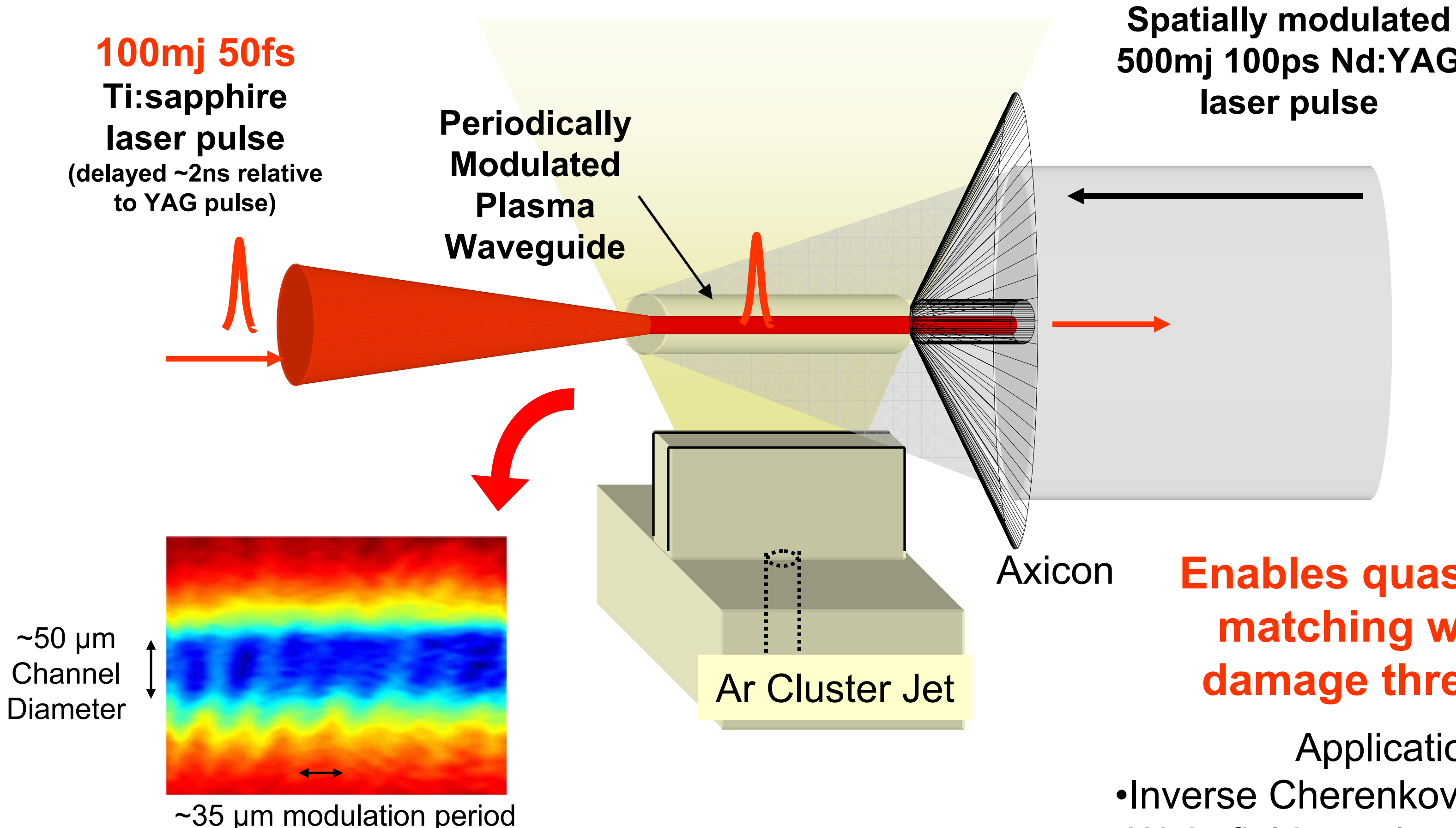


moderate intensity
fibre generating pulse:
100-500 mJ, 1.064 um
100 ps

- U. Maryland
- LBNL
- U. Texas



A periodically modulated preformed plasma channel for quasi-phase matched guiding



Extracted phase from 60fs transverse probe
(200 consecutive shot average, 1ns delay)

Enables quasi-phase matching with no damage threshold!

Applications:
- Inverse Cherenkov acceleration
- Wakefield acceleration
- High harmonic generation
- Terahertz generation

This method is flexible and works for a wide variety of gas targets and modulation periods

Atmospheric air spark

~1 mm corrugation period

Argon cluster jet spark

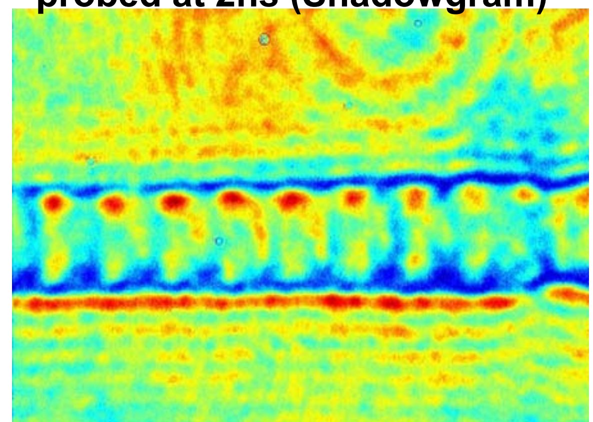
~1 mm corrugation period

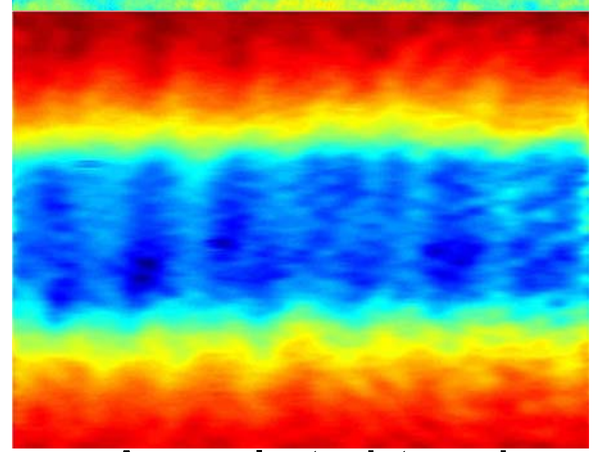
Different gas jet and laser beam parameters allow easy control of nearly every aspect of the waveguide:

- **Corrugation period**
- **Corrugation depth**
- **Waveguide size**
- **Electron density**
- **Degree of ionization**

Atmospheric air spark

~35 µm corrugation period probed at 2ns (Shadowgram)





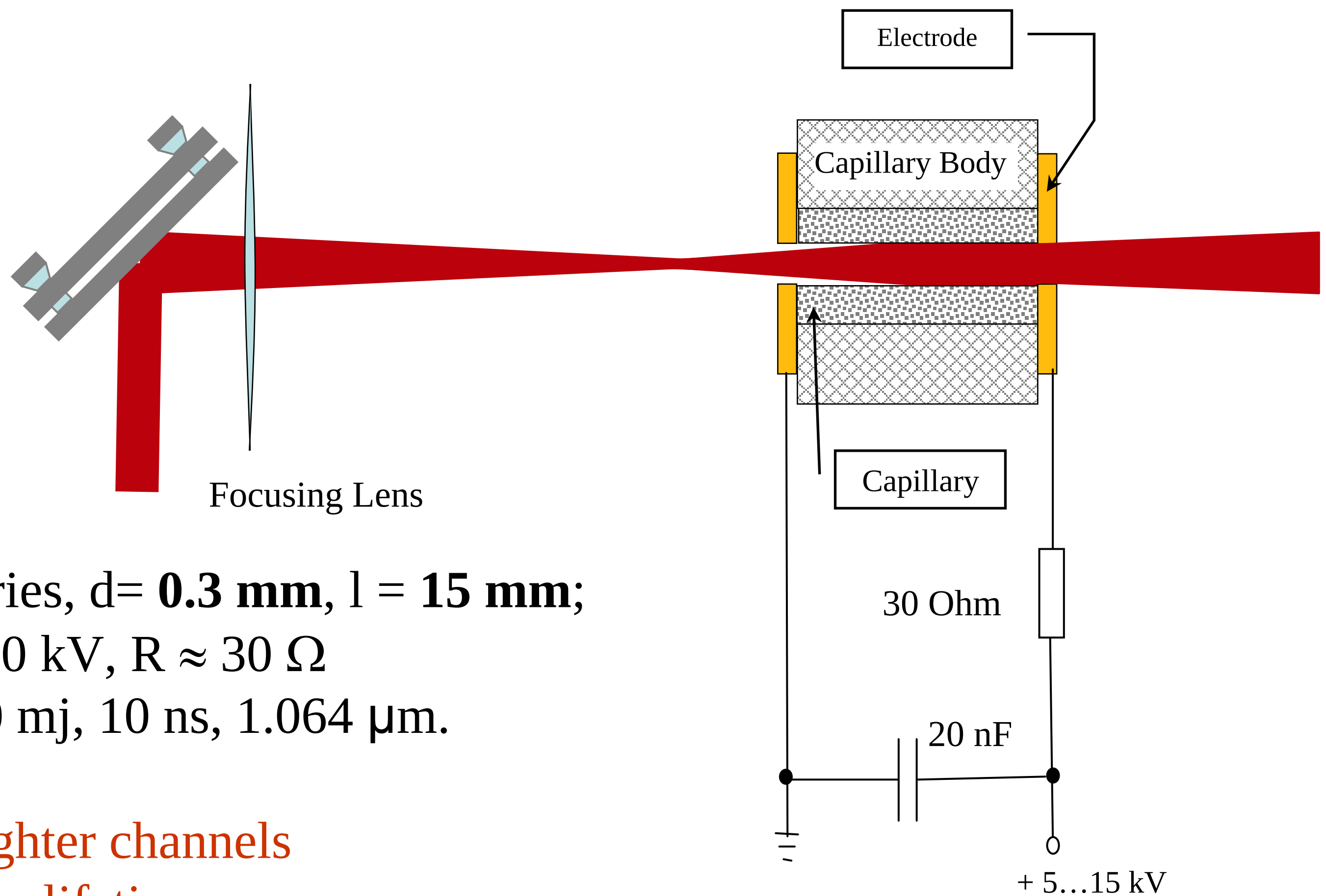
Argon cluster jet spark

~35 µm corrugation period probed at 2ns (Extracted interferogram phase)

ABLATIVE WALL CAPILLARY DISCHARGE

Setup with Laser Triggering

- Hebrew U.
- NRL
- BNL



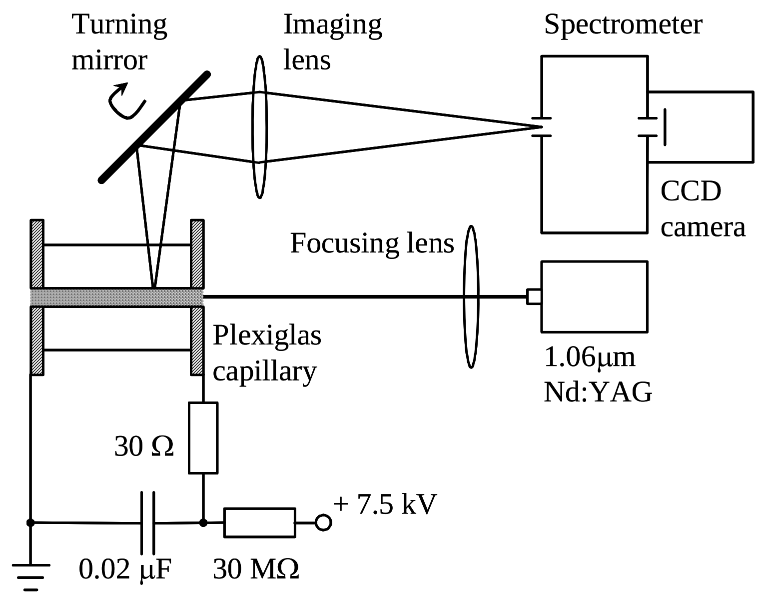
Polyethylene capillaries, d= **0.3 mm**, l = **15 mm**;
C = 20 nF, U = 5 – 10 kV, R ≈ 30 Ω
Laser ignition: 10-20 mj, 10 ns, 1.064 μm.

- Reduced jitter
- Lower density, tighter channels
- Much long caillary lifetimes

GUIDING EXPERIMENTS USING PLEXIGLAS CAPILLARY DISCHARGE

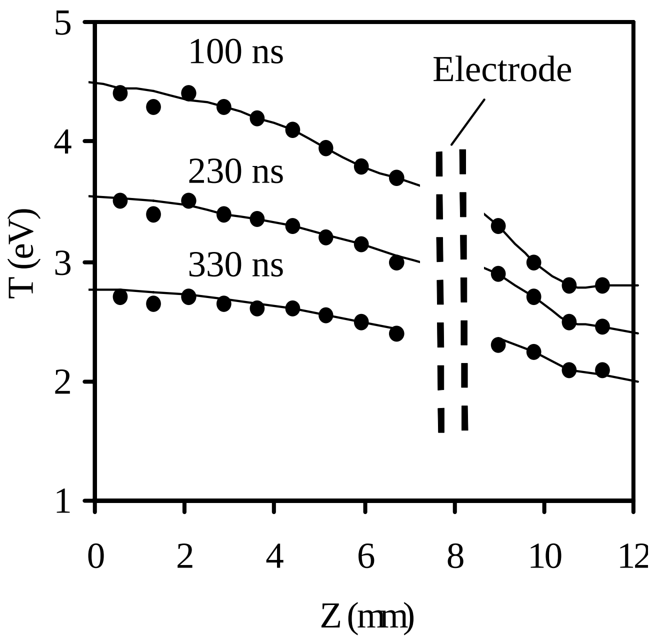
- Capillary triggered using laser ignition technique
- Plexiglas capillary allows imaging inside capillary
- Plasma temperature estimated from the relative intensities of singly-ionized emission lines: C II 462.7 nm and C II 387.6 nm
- Electron density determined from broadening of the H_α line
- Density variation also measured just outside capillary
- Recent experiments have extended channel length to 12.6 cm (submitted to Phys. Plasmas) and 20 cm (unpublished)

Experimental Setup

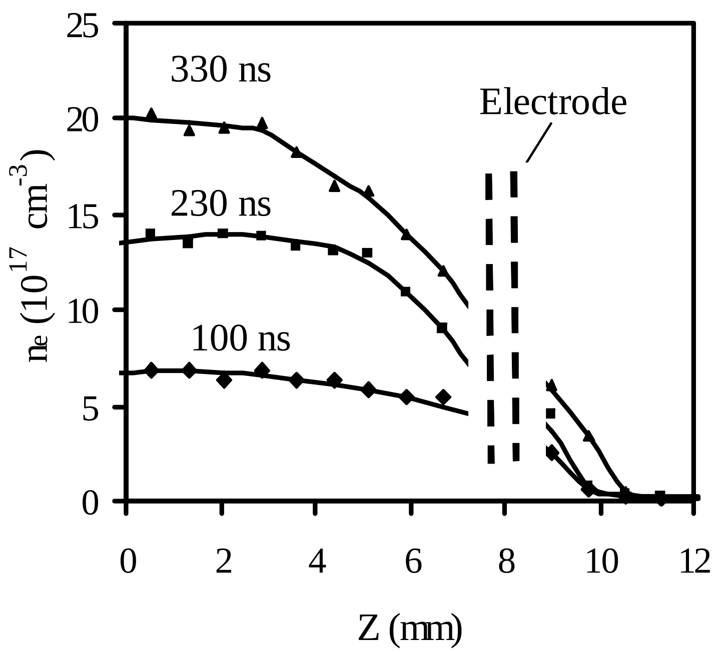


PLASMA DENSITY AND TEMPERATURE VARIATION IN PLEXIGLAS CAPILLARY

Temperature



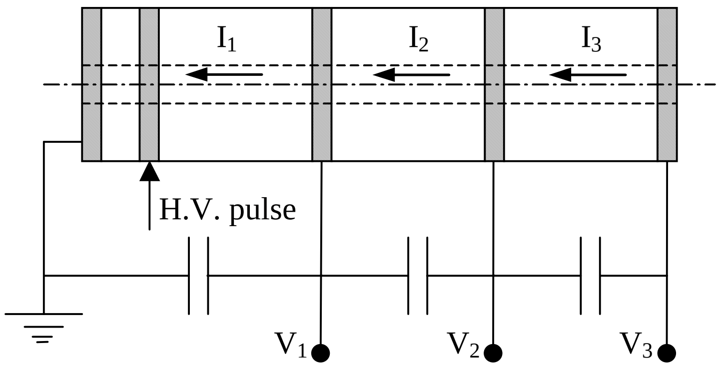
Density

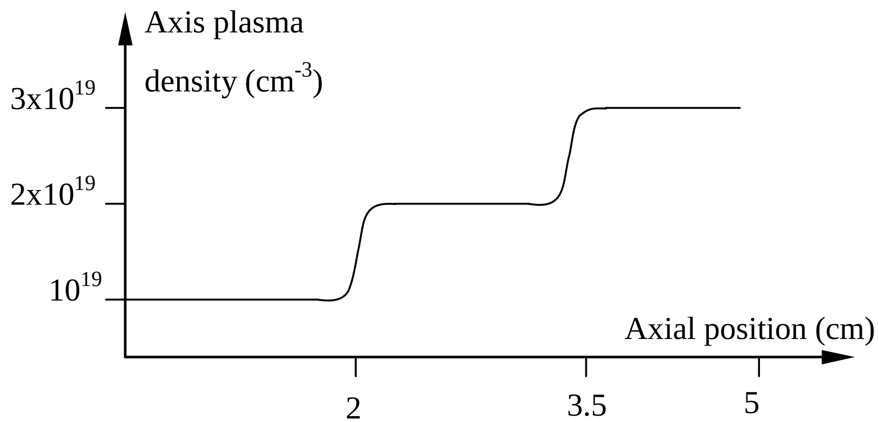


- Scans taken at three different delay times from discharge initiation
- 100 ns case has density suitable for a CGS-LWFA
- Previous work (square capillary): T. Jones, et al., Phys. Plasmas (2003)

SEGMENTED CAPILLARY DISCHARGE FOR GENERATING VARIABLE DENSITY CHANNELS

D. Kaganovich, A. Zigler (Hebrew University)





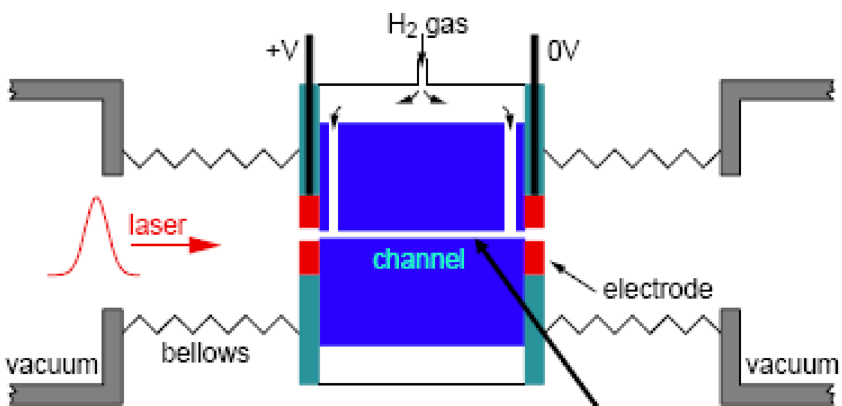
- Capillary segments have independent voltages
- Plasma density scales with voltage or current in each segment
- Can be used to increase dephasing-limited energy gain in resonant LWFA
- May be used to create very long (> 10 cm) channels for > 1 GeV LWFA (or PWFA?)

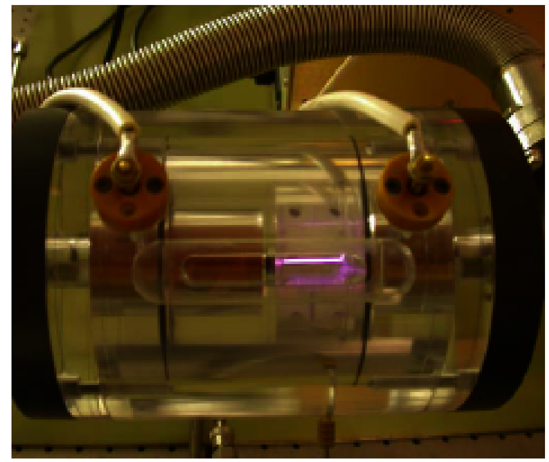
GAS-FILLED SLOW CAPILLARY DISCHARGE

Setup

Gas-filled capillary discharge waveguide: Overview

D. J. Spence *et al. Phys. Rev. E* **63** 015401(R) (2001)





- Channel 200 - 400 μm diameter
- Gas injected near each end of channel

- Gas ionized by pulsed discharge
  - Peak current 100 - 500 A
  - Rise-time 50 - 100 ns

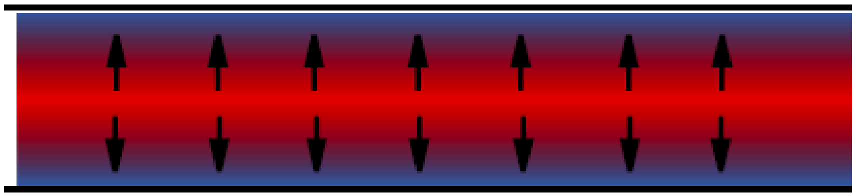
Capillary is alumina or sapphire: little ablation of walls in discharge

GAS-FILLED SLOW CAPILLARY DISCHARGE

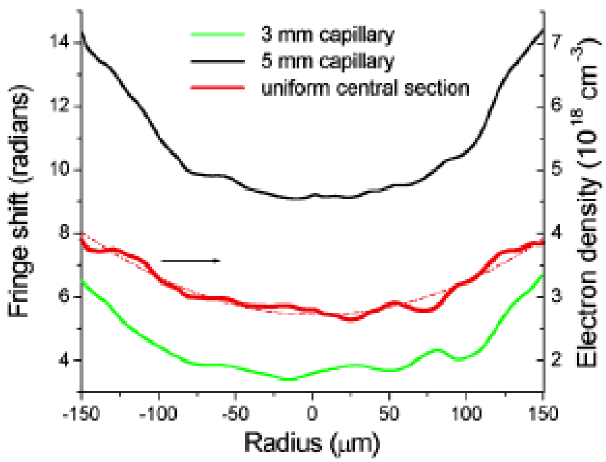
Channel Formation Process

Gas-filled capillary discharge waveguide: Formation of channel

D. J. Spence *et al. Phys. Rev. E* **63** 015401(R) (2001)
N. A. Bobrova *Phys. Rev. E* **65** 016407 (2001)



– Plasma profile formed by thermal conduction to cold capillary wall.



Measured electron density profile

- Initial H_2 pressure 63 mbar.
- Parabolic density profile. Matched spot size of 37 μm.
- Fully ionized hydrogen

• **Used in recent GeV LWFA experiments at LBNL**

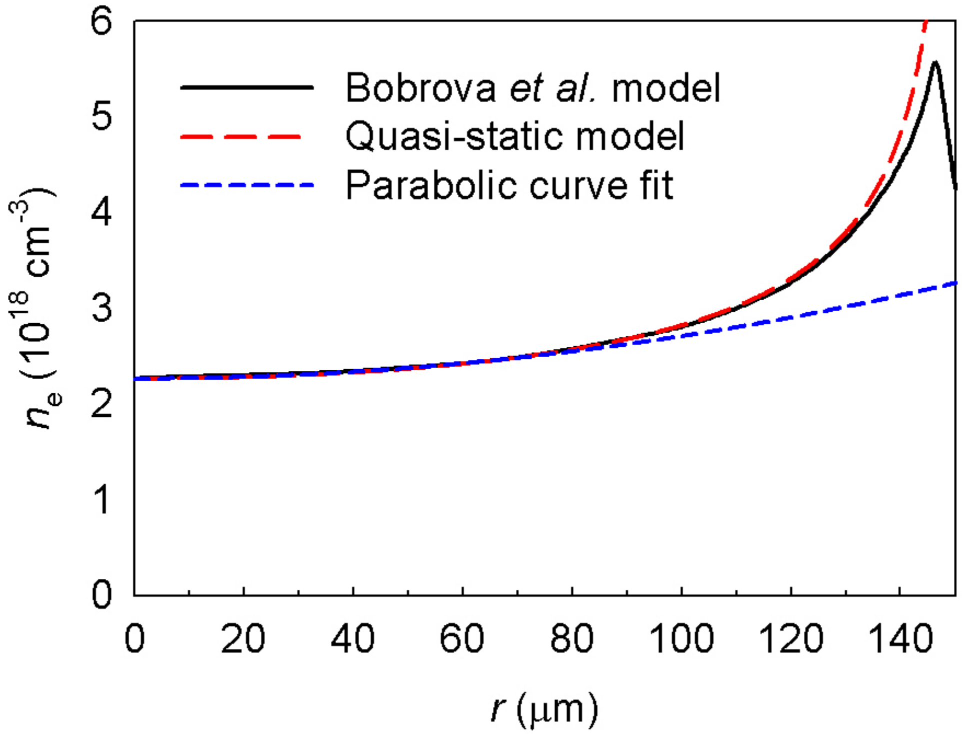
GAS-FILLED CAPILLARY DISCHARGE

Quasi-static Numerical Model

Assumptions

- Quasi-steady-state
- Quasi-neutrality with static ions
- Pure hydrogen as gas
- Single plasma temperature
- Negligible parasitic losses
- Braginskii transport

Plasma Density Profile

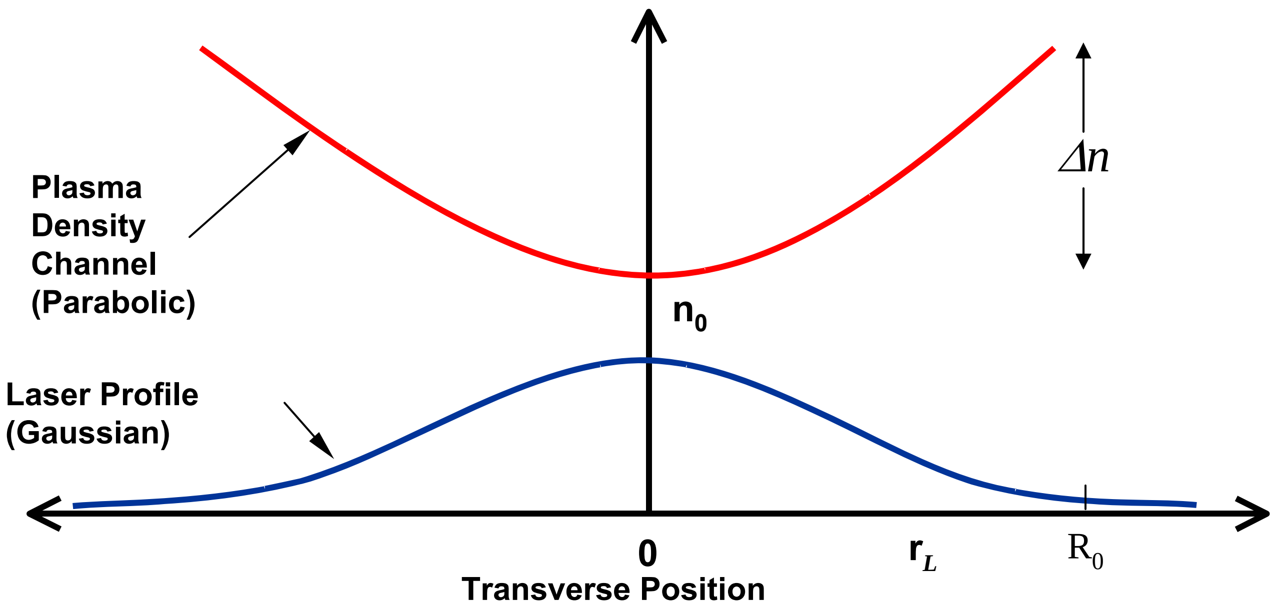


- Bobrova model: Time-dependent magnetohydrodynamic (MHD)
- Sasorov has MHD model for ablative wall discharges

W. Kimura

OPTICAL GUIDING IN PLASMA CHANNELS

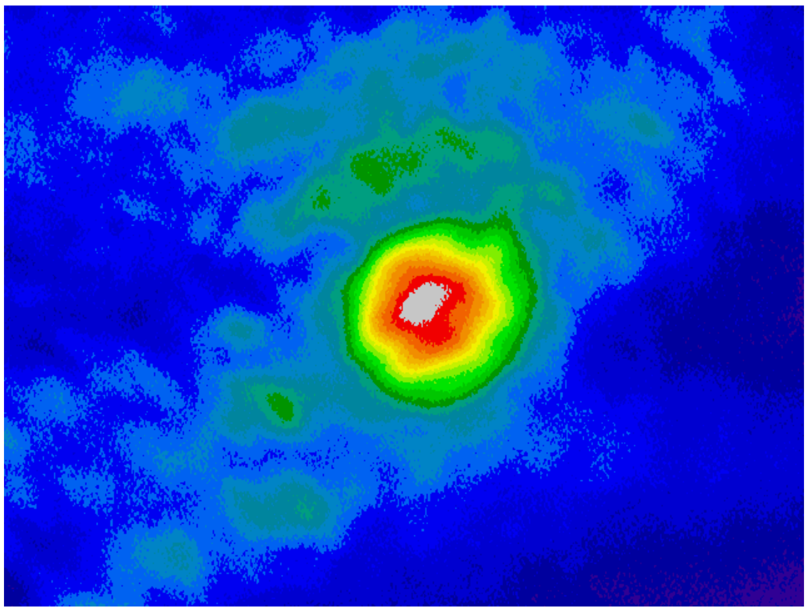
Theory for ideal channel and beam



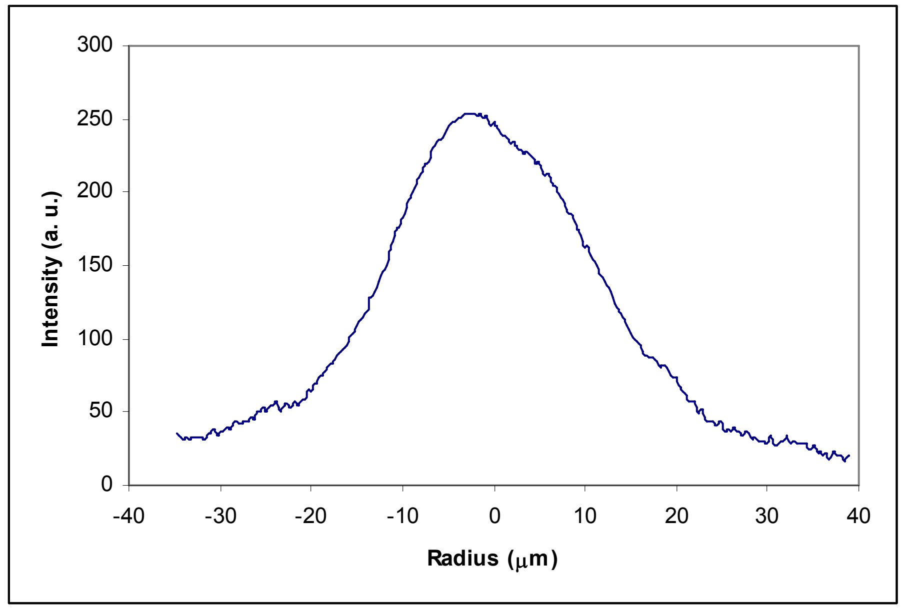
- In vacuum, beam injected with Gaussian radius r_0 expands over characteristic distance (Rayleigh length) given by $Z_R = \pi r_0^2/\lambda$
- For channel parabolic out to radius R_0, equilibrium laser spot size is $r_M = (R_0^2/\pi\, r_e \Delta n)^{1/4}$, where Δn is channel depth, $r_e = 2.8 \times 10^{-13}$ cm
- Laser radius $r_L(z)$ oscillates around r_M, may guide for many Rayleigh lengths

HIGH RESOLUTION GUIDING IMAGE NRL T³ LASER

300 μm diameter capillary, 1 TW laser power,
20 μm matched spot size, > 70% transmission efficiency

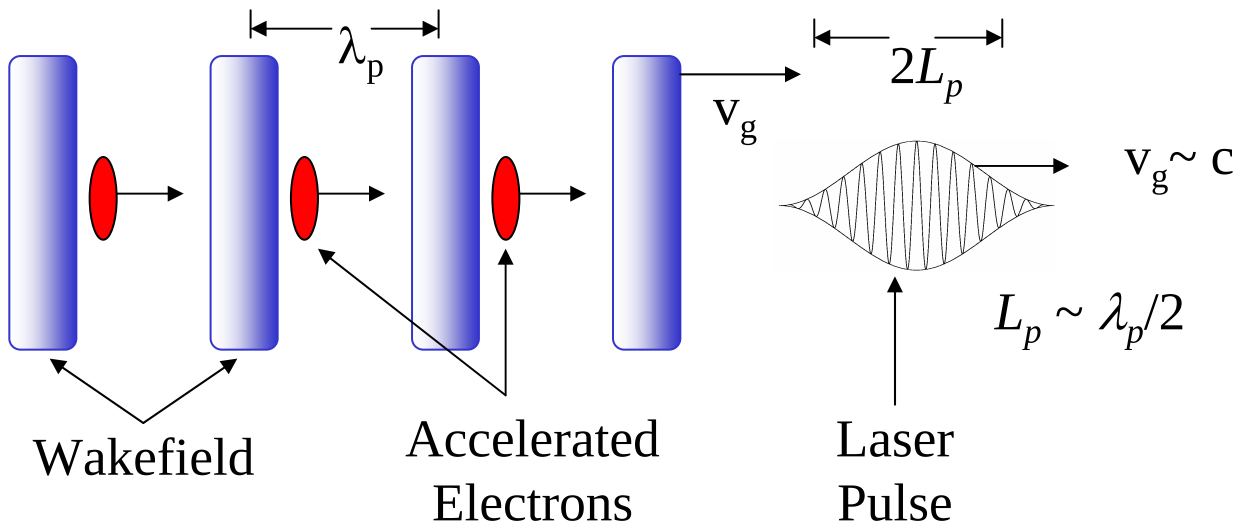


150 μm



Tighter, high intensity guided pulse – improves LWFA performance and lowers required minimum electron energy for injection

LASER WAKEFIELD ACCELERATION (LWFA) – Standard Regime

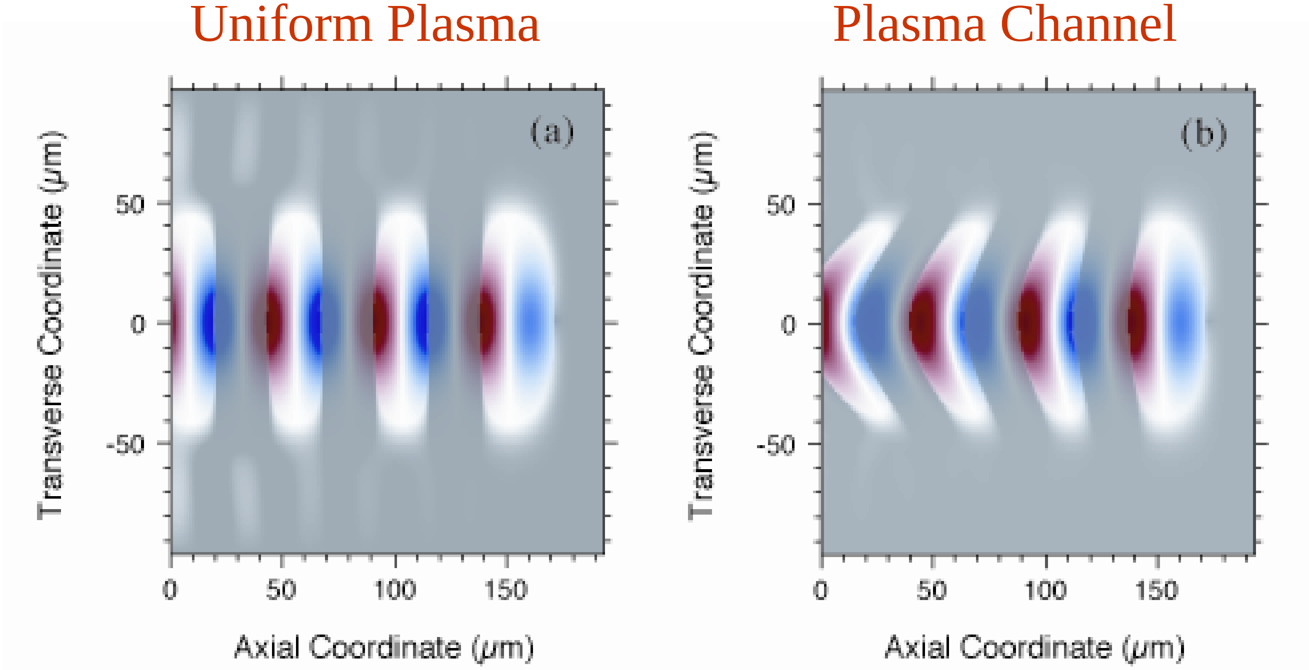


- Laser pulse creates large amplitude plasma wave whose phase velocity is approximately the laser pulse group velocity v_g
- *Standard regime:* Laser pulse length L_p shorter than the plasma wavelength $\lambda_p = 2\pi c/\omega_p$
- Plasma channel can provide optical guiding to extend acceleration length

FOCUSING AND DEFOCUSING REGIONS OF WAKE PHASE

TurboWAVE simulation showing transverse and longitudinal electric field

Uniform Plasma　　Plasma Channel



- White regions are focusing; red/blue regions are accelerating/decelerating
- In a uniform plasma, radial electric field is focusing for phases satisfying $0 < \psi < \pi \pmod{2\pi}$
- Focusing/accelerating phase region in channel is shifted significantly and enlarged

Road Map to a Table-Top , Multi-GeV, High Quality Laser Accelerator

Pre-2004

Standard LWFA ($c\tau_L < \lambda_p$, $r_o > \lambda_p$)
Moderate Intensity ($I < 10^{18}$ W/cm^2)
Phased, mono-energetic external injection
Channel guiding

Phased,
Mono-Energetic
Injection
(Beam Quality)

~1 MeV

Guided Acceleration
in Plasma Channel
(Diffraction)

E_{acc} ~ 10 GV/m

~ GeV

Tapered
Plasma Channel
(Dephasing)

E_{acc} ~ 10 GV/m

~ 5 GeV

Staging
(Energy Depletion)

~ 5xN GeV

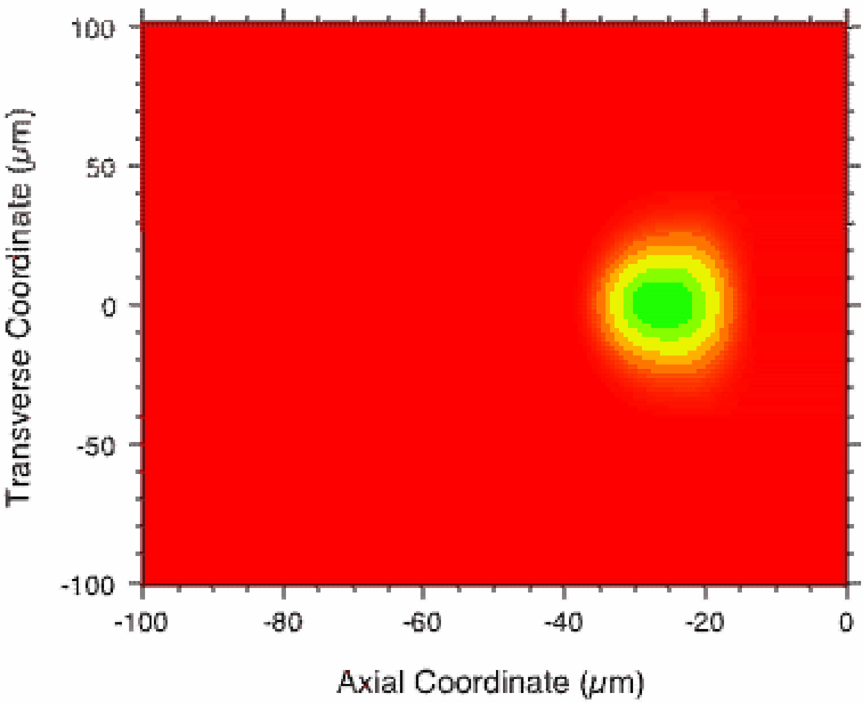
P. Sprangle, AAC, 2002

CHANNEL-GUIDED LWFA SIMULATION

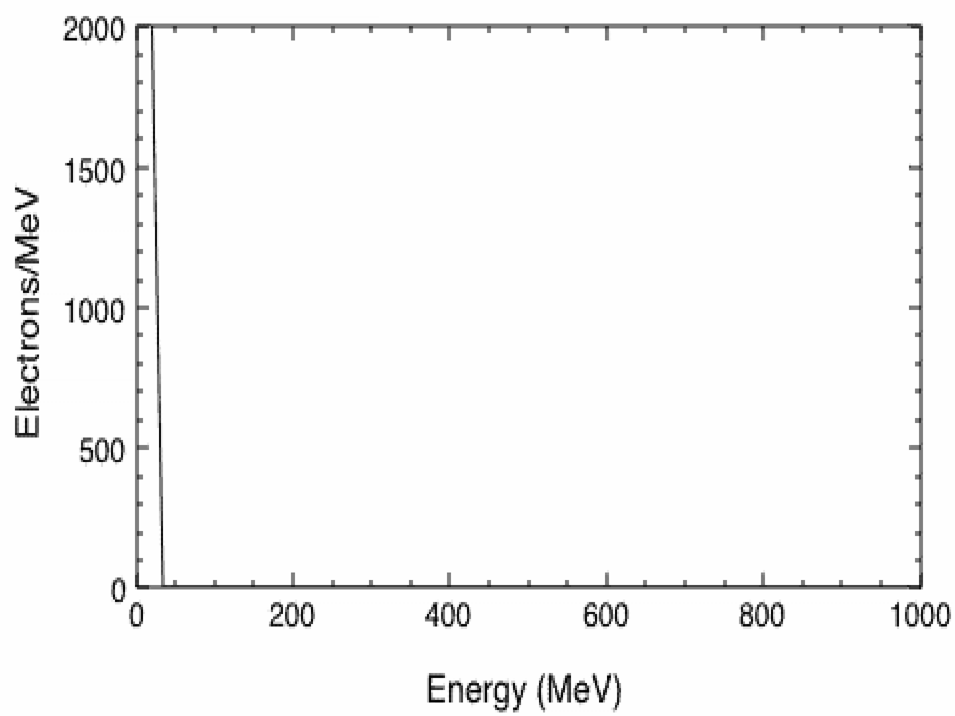
‘End-to-End’ TurboWAVE Simulation of NRL Design

- **Design: 2 TW ‘LIPA’ injector, 8 TW LWFA drive pulse, 3-stage segmented capillary discharge channel**
- **Simulation: Pulse well-guided in channel, show group velocity slippage**
- **Simulation: Produces quasi-monoenergetic beam, W ~ 800 MeV at end**

Driving Laser Pulse



Electron Energy Spectrum



D. Gordon, AAC, 2004

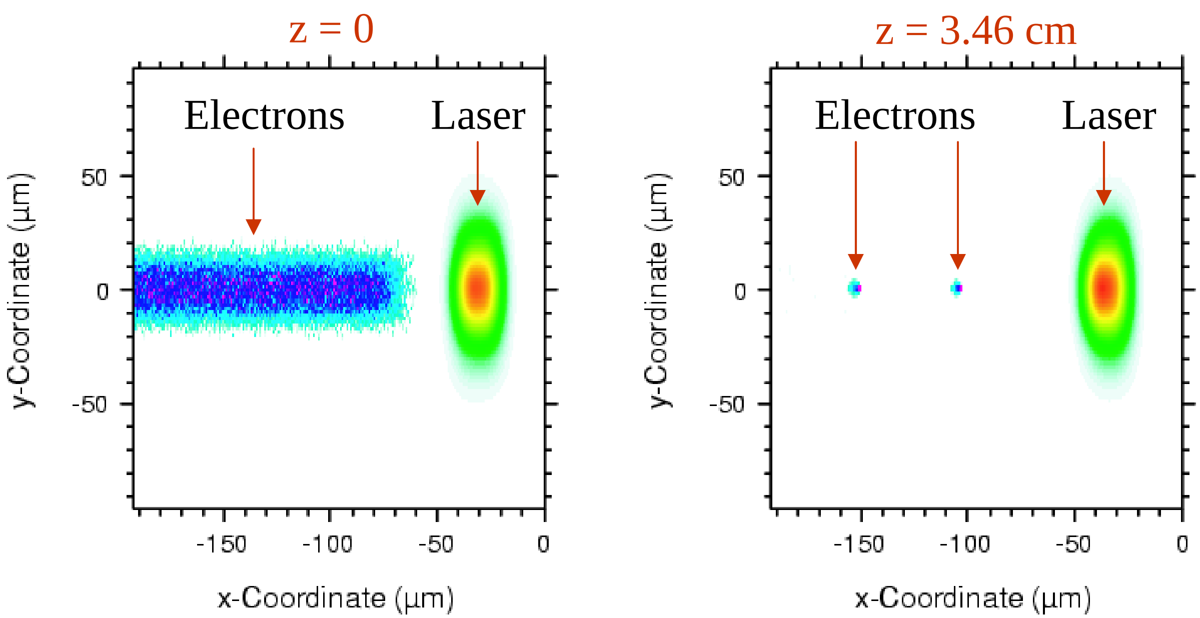
‘ROADMAP’ OVERTAKEN BY EVENTS
Quasi-monoenergetic beams

- Nonlinear (Forced) LWFA (bubble) regime experiments
  - No external injection, gas jet
  - Significant pump depletion and pulse distortion
  - Demonstrated at RAL, LOA, many others
- Channel-guided LWFA experiments
  - No external injection, electrons originate from channel plasma
  - Demonstrated at LBNL: >1 GeV seen, reliable 500 MeV
- Nonideal injection theory (NRL)
  - Unphased, monoenergetic injection
  - Warm beam injection
- However, ‘roadmap’ with phased injection may still be necessary for applications requiring high beam quality

LWFA IN CHANNEL WITH INJECTION OF UNPHASED ELECTRONS

TurboWAVE Simulation

- Laser: P_0 = 8 TW, λ = 0.8 μm, τ_L = 80 fsec, r_0 = 30 μm
- Channel: n_0 = 5x10^{17} cm^{-3}, density profile matched to r_0
- Injected electrons: W_0 = 1.6 MeV, uniform phase distribution, ε_n = 1 π mm-mrad



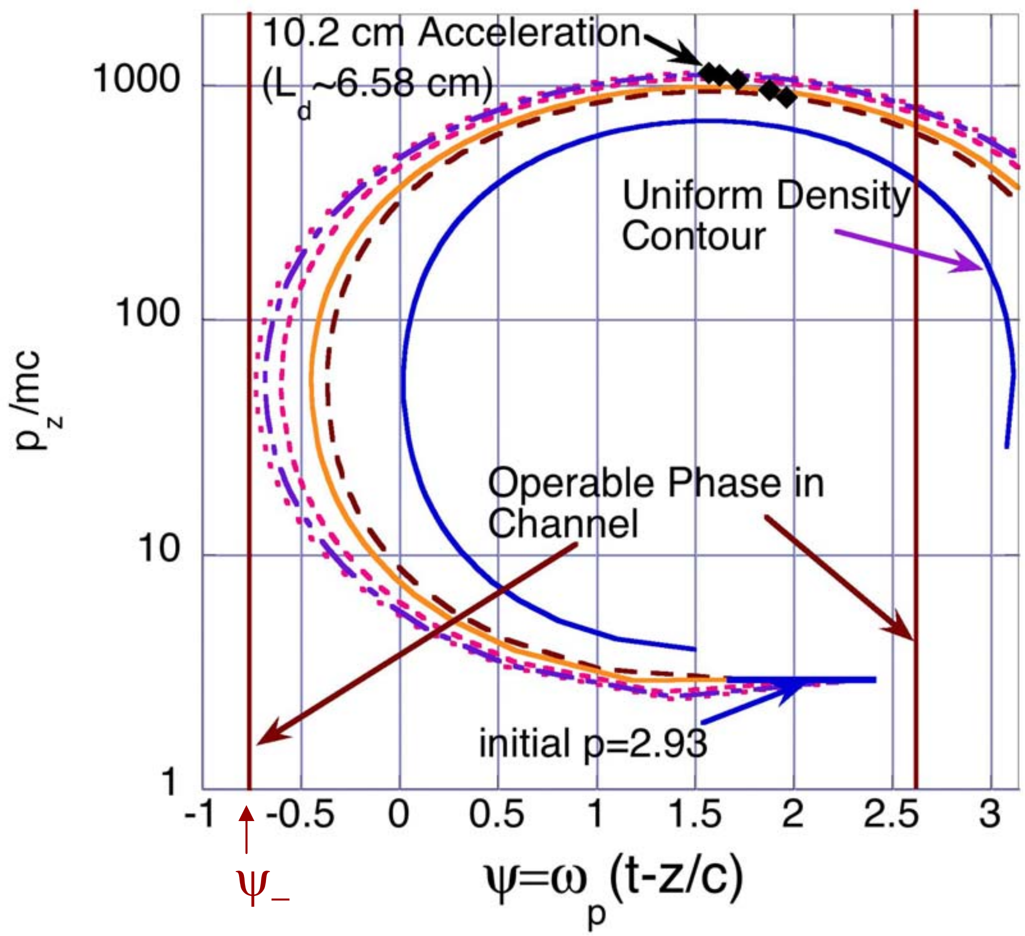
- Produces very narrow, well-focused electron bunches with modest energy spread
- Results agree with Hamiltonian model (D. Gordon, PRE **71**, 026404 (2005).

HAMILTONIAN MODEL FOR ACCELERATION AND TRAPPING IN LWFA

n_0 = 5x10^{17} cm^{-3}, ϕ_0 = 0.1, P_0 = 8 TW, λ = 0.8 μm, r_0 = 30 μm

- Ideal sinusoidal wake
- Focusing region in *uniform plasma*: $0 < \psi < \pi$ (Blue)
- Focusing region in *plasma channel*: $-0.75 < \psi < 2.57$ (From TurboWAVE)
- Phase space orbits shown for unphased, monoenergetic injection in plasma channel at $p_z/mc^2 = 2.93$
- Allowable injection energy is significantly reduced
- Final energy and dephasing length are larger
- Small final energy spread

Phase Space Trajectories

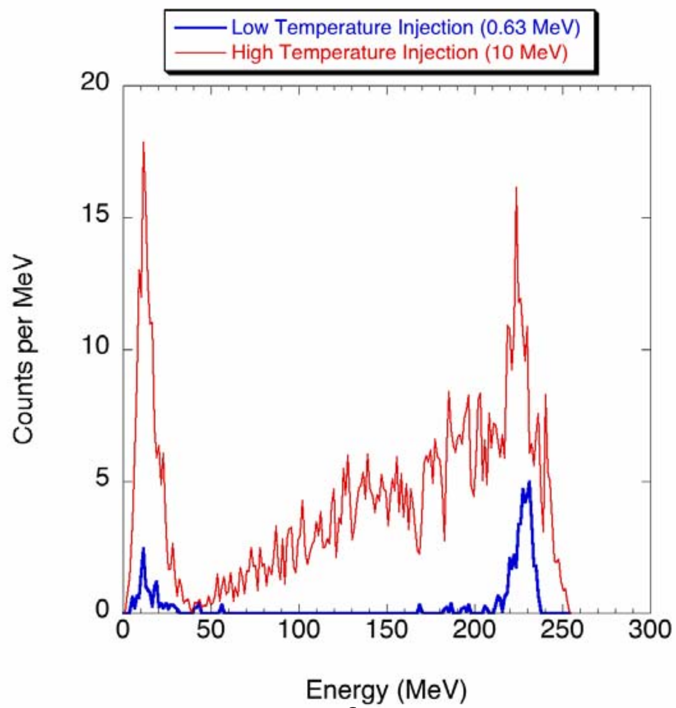


UNPHASED, WARM BEAM INJECTION

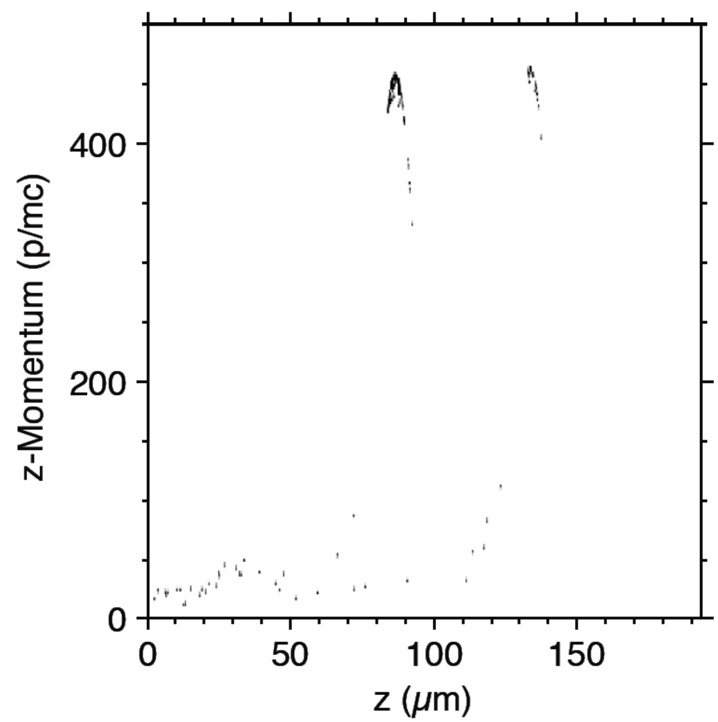
TurboWAVE Simulation, *ct* = 3.3 cm

R. Hubbard, IEEE Trans. Plasma Sci. 33, 712 (2005)

Distribution functions



Phase Space (T_{inj} = 0.63 MeV)



- P_0 = 8 TW, τ_L = 67 fs, r_0 = 30 μm, n_0 = 5x10^{17} cm^{-3}, λ = 0.8 μm
- Injection bunch loaded over 2π in phase; Maxwellian with T_{inj} = 0.63 MeV, 10 MeV
- High temperature injection gives much greater trapping *but* broad final energy spread
- More intense lasers require <100 keV injection energies

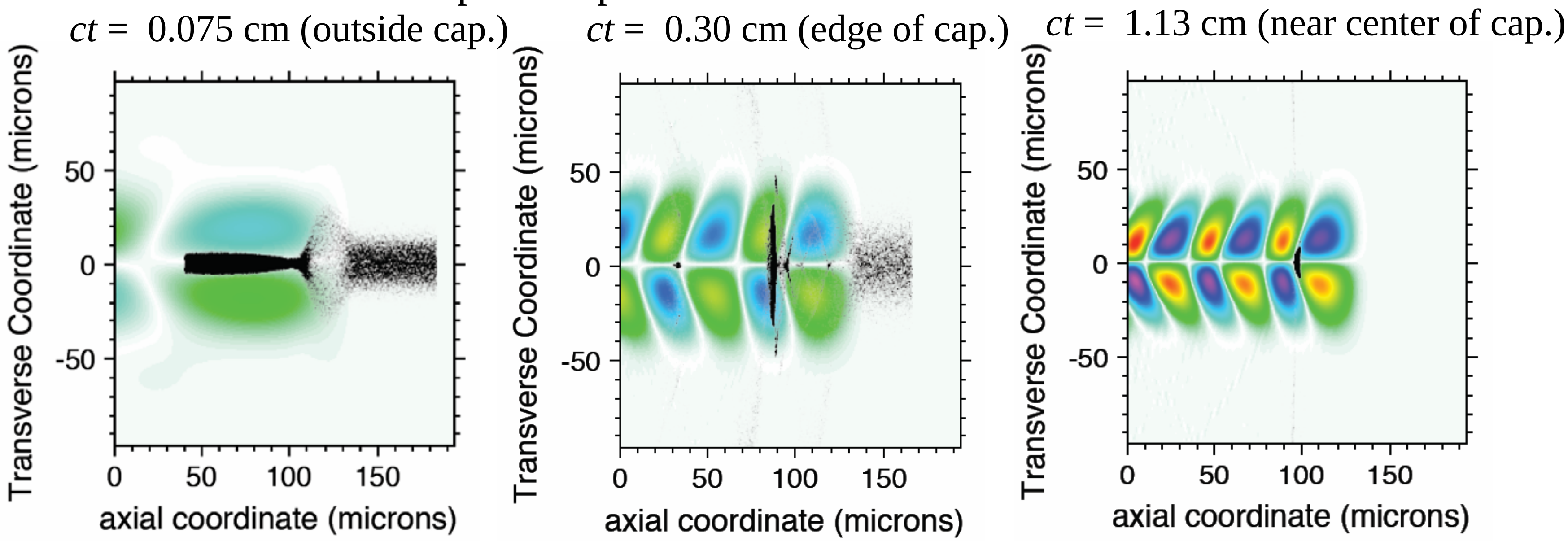
TRAPPING AND ACCELERATION OF INJECTED ELECTRONS IN CAPILLARY WITH AXIALLY-VARYING DENSITY

TurboWAVE simulation with 100 ns density profile (experimental)

•Parameters: P_0 = 16 TW, r_m = 30 μm, λ = 0.8 μm; W_0 = 3.5 MeV (injected electrons)

•Plots show E_y (ζ, y) contours in beam frame; blue is positive (focusing for y > 0)

•Black dots denote test particle positions



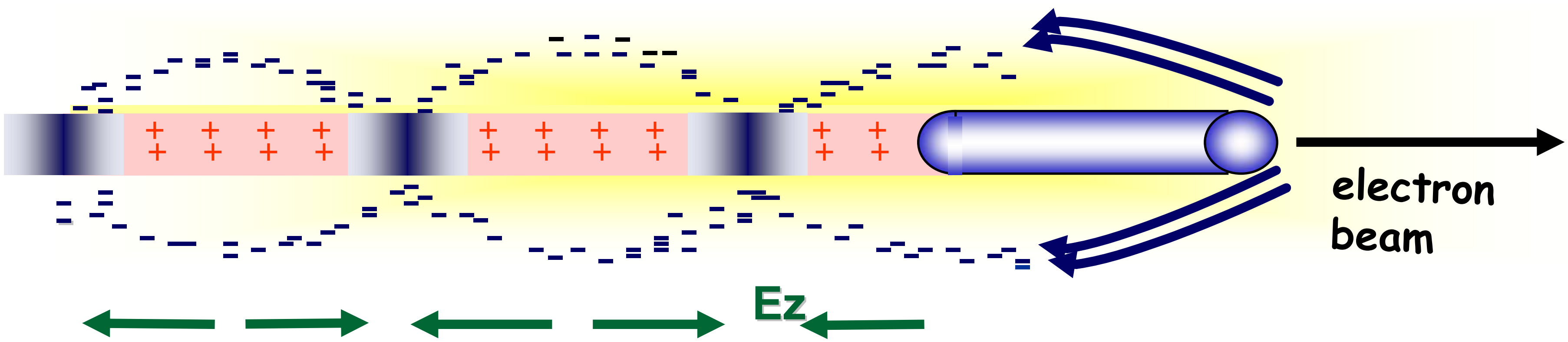
- Wakefield strength increases, wavelength decreases as density ramps up with *ct*
- Trapping seen only in first wakefield bucket

EFFECT OF DENSITY RAMP ON INJECTION OF ELECTRONS INTO CAPILLARY

- Introducing a long density gradient at the entrance into the plasma channel introduces two problems
  - Low initial accelerating gradients – modest energy electrons may be left behind before being sufficiently accelerated
  - Wavelength of wakefield changes continuously – electrons in all but first bucket pass through defocusing regions even if W_0 is high
  - This raises minimum energy for trapping significantly
- Potential solutions
  - Reduce density gradient length in capillary-vacuum transition region
  - Increase injection energy or laser intensity
  - Use *internal* injection so that injected electrons originate inside capillary (may have occurred in recent LBNL experiments)

Plasma Wakefield Accelerator

- Space charge of drive beam displaces plasma electrons



- Plasma ions exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake on a boat)
- Wake amplitude $\boxed{\propto N_b / \sigma_z^2}$ $\left(\textit{for } 2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_o}} \right)$

P. Muggli

PLASMA CHANNELS AND PWFA

Motivation

- Current experiments at SLAC use and direct e-beam (tunneling) ionization to create plasma column with $n \sim 10^{17}$ cm^{-3}
  - This ‘self-channeling’ method is relatively simple to implement and ***spectacularly successful*** – provides both guiding and wakefield acceleration
- Potential difficulties with direct e-beam ionization
  - Can only be used at extreme beam intensities on *very* large facilities
  - Less effective for positron beams – hollow channel preferred
  - Very limited control over radial profile of plasma density – uniform radial profile in region near beam axis
  - Ion channel collapse identified as a serious potential problem, particularly for next generation collider (ILC) – Rosenzweig, et al, PRL 2005
  - Electron hose instability, if encountered, will be an absolute instability with limited knobs to control
- Capillary discharge plasma channels have been used in PWFA experiments at Brookhaven in *overdense* regime (V. Yakimenko)

SEGMENTED CAPILLARY DISCHARGES FOR PWFA APPLICATIONS

- Desirable features for future PWFA experiments
  - Plasma density matched to drive beam pulse length (>10^{17} cm^{-3} for current SLAC experiments)
  - Potentially extendable to several meters in length
  - Ability to generate hollow plasma density profile – desirable for positron drive beam and (possibly) ion channel collapse prevention
  - Ability to generate "solid" plasma channel profile – may convert electron hose instability to a convective instability with much reduced growth[1]
- Segmented capillary discharges with periodic electrodes may provide such a plasma
  - Demonstrated experimentally by Zigler's group (Hebrew Univ.)
  - Optical guiding demonstrated in single stage discharges up to 20 cm
  - Proposed for long, tapered channels for LWFA applications
  - Ablative wall versions demonstrated; gas-filled may be required for high rep rate applications

[1]M. Lampe, et al., Phys. Plasmas (1993)

RELATIONSHIP OF PWFA TO DOD HIGH CURRENT ELECTRON BEAM PROPAGATION PROGRAMS (1980-1995)

- Laser guided propagation in space (DELPHI)[1]
  - Laser ionization of atomic oxygen, *ion focused transport*
  - Key issues: electron hose instability, ion channel motion, wakefield coupling to beam head erosion
- Propagation of Ultrarelativistic Electrons (PURE)[2]
  - Train of extremely small (1 μm) pulses; bore hole in air, *ion focused transport*
  - Key issues: electron hose instability, resistive hose instability, beam head erosion, scattering, synchrotron losses
- High current (>10 kA) long pulse propagation in air
  - Used *ion focused transport* for beam shaping, damping hose seeds
  - Key issues: resistive hose instability, channel tracking, beam head erosion, scattering

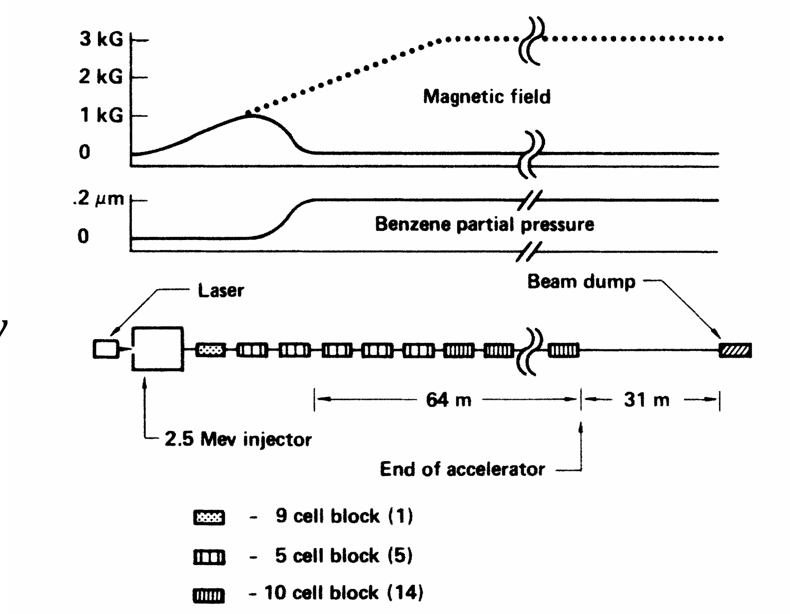
[1]R. B. Miller (Sandia); H. L. Buchanan (LLNL/DARPA/ASN); [2]S.S. Yu, W. Fawley, LLNL

ION CHANNEL GUIDING OF ELECTRON BEAMS IN ACCELERATORS

Advanced Test Accelerator (ATA)
Lawrence Livermore National Laboratory

- 45 MeV, 1-10 kA, 50-70 nsec pulse, 1 Hz
- Induction linac with KrF laser; 100 m long benzene plasma channel
- Used for atmospheric propagation experiments and SDI free electron laser
- Beam breakup instability (BBU) was a severe problem for solenoidal transport
- ***Ion channel*** provided guiding and *greatly* reduced BBU
- Emittance growth observed in back of pulse – attributed to ion channel motion
- Channel also used for post-accelerator beam conditioning to damp transverse fluctuations (seed for hose instability)

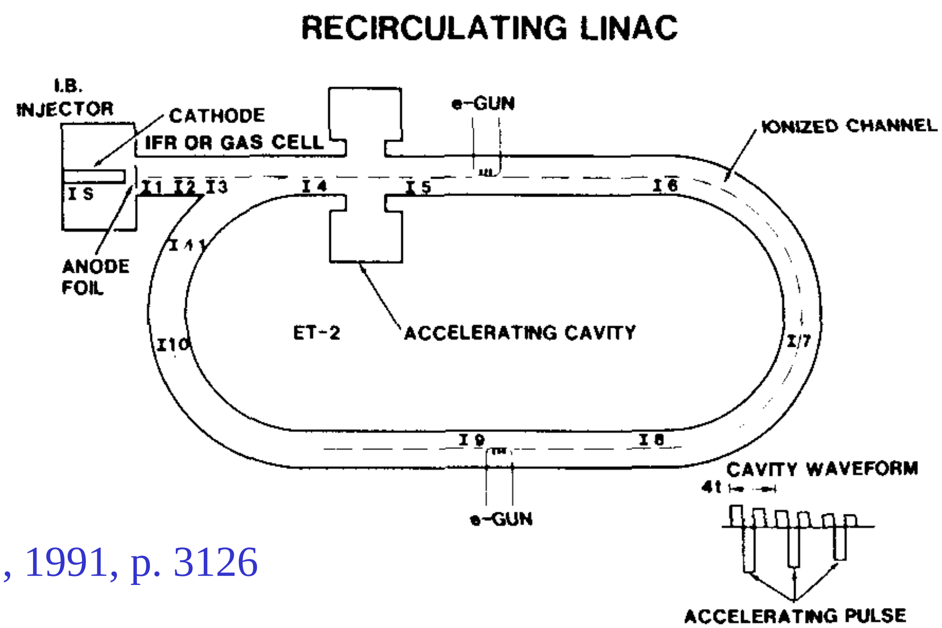
G. Caporaso, *et al*, PRL **57,** 1591 (1986)



ION CHANNEL GUIDING OF ELECTRON BEAMS IN ACCELERATORS

Recirculating Linear Accelerator (RLA)
Sandia National Laboratories

- Intended as a compact, recirculating version of ATA
- Racetrack **ion channel** produced by low voltage electron beam ionizing low density fill gas
- Channel guiding aided by bending magnets in curved sections
- Major issue: ion channel motion after multiple passes (fatal flaw?)
- Single pass guiding demonstrated; project ended



M. Mazarakis, *et al*, Part. Accel. Conf., 1991, p. 3126

SUMMARY

- For accelerator applications, plasma channels can provide
  - Guiding or focusing of drive beam: laser or particle beam
  - Medium for plasma-based acceleration
- Several techniques for generating plasma channels have been demonstrated experimentally
  - Substantial recent progress: longer, lower density channels; clusters
- Optical guiding in hollow plasma channels
  - Key component of traditional ‘roadmap’ for GeV-class LWFA
  - Alternatives to this roadmap have recently emerged
  - Major milestone: GeV acceleration in plasma channel demonstrated
- Plasma channels may also be useful for plasma wakefield accelerators (PWFA)